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HESS II Data Analysis with ImPACT

R.D. Parsons*
Max-Planck-Institut für Kernphysik, P.O. Box 103980, D 69029, Heidelberg, Germany
E-mail: daniel.parsons@mpi-hd.mpg.de

M. Gajdus
Institut für Physik, Humboldt-Universität zu Berlin, Newtonstr. 15, D 12489 Berlin, Germany
E-mail: mgajdus@physik.hu-berlin.de

T. Murach
Institut für Physik, Humboldt-Universität zu Berlin, Newtonstr. 15, D 12489 Berlin, Germany
E-mail: murach@physik.hu-berlin.de

on behalf of the H.E.S.S. Collaboration

The High Energy Stereoscopic System (H.E.S.S.) very high energy gamma-ray telescope array has added a fifth telescope of 600 m^2 mirror area to the centre of the 4 existing telescopes, lowering its energy threshold to the sub-100 GeV range and becoming the first operational IACT array using multiple telescope designs. In order to properly access this low-energy range however, some adaptation must be made to the existing event analysis.

We present an adaptation of the high-performance event reconstruction algorithm, Image Pixel-wise fit for Atmospheric Cherenkov Telescopes (ImPACT), for performing mono and stereo event reconstruction with the H.E.S.S. II array. The reconstruction algorithm is based around the likelihood fitting of camera pixel amplitudes to an expected image template, directly generated from Monte Carlo simulations. This advanced reconstruction is combined with a multi variate analysis based background rejection scheme to provide a sensitive and stable analysis scheme in the sub-100 GeV gamma-ray energy range. We will present the latest results of the ImPACT analysis on both simulated and real H.E.S.S. II data, demonstrating the behaviour of the ImPACT analysis at the lowest energies.

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*Speaker.

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1. Introduction

In ground-based gamma-ray astronomy a necessary step before the analysis of astronomical data is the reconstruction of observations made of gamma-ray induced air showers, to determine the properties of the initial very high energy photon. Traditionally such reconstruction has been performed using a simple parameterisation of the roughly elliptical gamma-ray image seen in imaging atmospheric Cherenkov telescope (IACT) cameras, using the first and second moments of the image. However, it has been shown that greatly improved performance can be achieved from IACTs by performing a more powerful maximum likelihood fit of the gamma-ray images to an expected image template [1, 2].

Here we will present an adaptation of the high performance ImPACT analysis [3] to work with the recently commissioned H.E.S.S. II IACT array. Such adaptation is required as an additional telescope of $\sim$600 m^2 (CT 5) has been added to the centre of the array, significantly reducing its energy threshold to below 50 GeV. This addition creates two new classes of events, which must be dealt with in the analysis. The *mono* event class is detected in CT 5 only and have the lowest energy threshold. *Stereo* events on the other hand are detected in CT 5 and at least one other telescope, requiring two telescope designs to be dealt with in the reconstruction process.

To demonstrate the performance of the ImPACT analysis on these different event classes, we will present the results of two event reconstruction types mono & stereo. Mono event analysis reconstructs all events using CT 5 only (removing information for other telescopes if present), while stereo analyses perform reconstruction with events having images in any two telescopes in the array.

2. Event Reconstruction

Before the event fit procedure can take place, first an image template library for the two telescope types must be created for a large number of fixed primary particle properties (energy, zenith angle, impact distance and depth of shower maximum). These templates are created using the same Monte-Carlo procedure described in [3], using detailed simulation of the behaviour of each telescope type.

2.1 Stereo Event Fitting

Once the template library has been created event fitting can begin in the same way as described for the H.E.S.S. I data analysis. A number of trial primary parameters for the gamma-ray are generated from the Hillas-parameter based analysis. At these trial positions the expected shower image can be created by performing a multi-dimensional interpolation of the template library and compared to the individual camera images using the likelihood function created in [2]. The primary particle properties can then be reconstructed by performing a multi-dimensional fit (source position in sky, impact position on the ground, energy and depth of shower maximum) using the MINUIT package [4].

The adaptations to this procedure to work with stereo events is minimal, requiring a new set of templates to be read for CT 5 camera images. Fitting is normally complete after 300-500 function calls, requiring around 0.5 seconds to perform the minimisation. All stereo results presented use

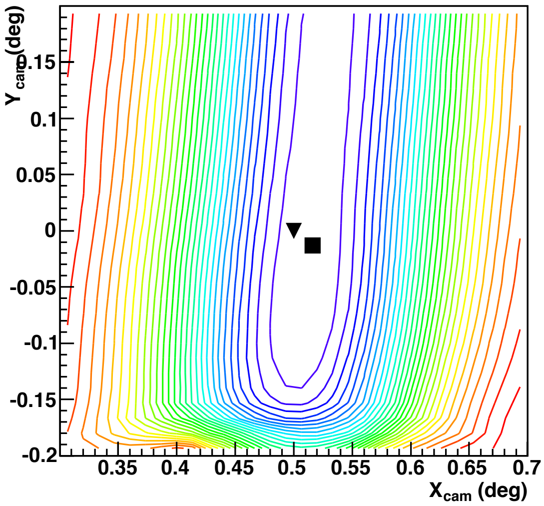

Figure 1: 2D slice of the likelihood surface of a mono event, shown in the camera reference frame, the black triangle represents the simulated source position and the black square the ImPACT reconstructed position.

simple box cuts on the Mean Scaled Width/Length parameters (described in [5]). Although this method of background rejection is rather simple it is well proven and quite robust, in the future background rejection will be improved by the use multivariate analysis similar to that presented in [6].

2.2 Mono Event Fitting

In order to make the ImPACT fit converge with events with only a single telescope image some adaptations to the fitting procedure were required. Firstly the standard stereo event analysis was no longer possible so a Hillas-parameter based mono telescope analysis is used to seed the fit [7]. In such a Hillas analysis there are two possible solutions to the reconstructed shower direction (Head-Tail ambiguity) so both of these starting points were tested and the highest likelihood starting position chosen. Once this starting position is chosen the full fit can begin, however in such a mono event analysis significantly less information is available for fitting, leading to a far less constrained likelihood surface (see Figure 1) and degeneracies in a number of fitted parameters. In order to avoid such degeneracies a two-step fitting procedure was adopted, with a first fit leaving all parameters free except X_{max} (fixed at the expectation value for the current energy) followed by a second fit fixing the source position and leaving all other parameters free.

Event fitting is somewhat faster than for stereo events, taking around 0.2 seconds per event. Background rejection for mono events is performed using a series of neural networks trained on Hillas parameters, described in detail in [7]. Mono analysis cuts were optimised at 3 cut levels, *safe, std & loose*. These cuts are optimised with differing levels of energy threshold (safe being highest and loose lowest) at the expense of overall performance.

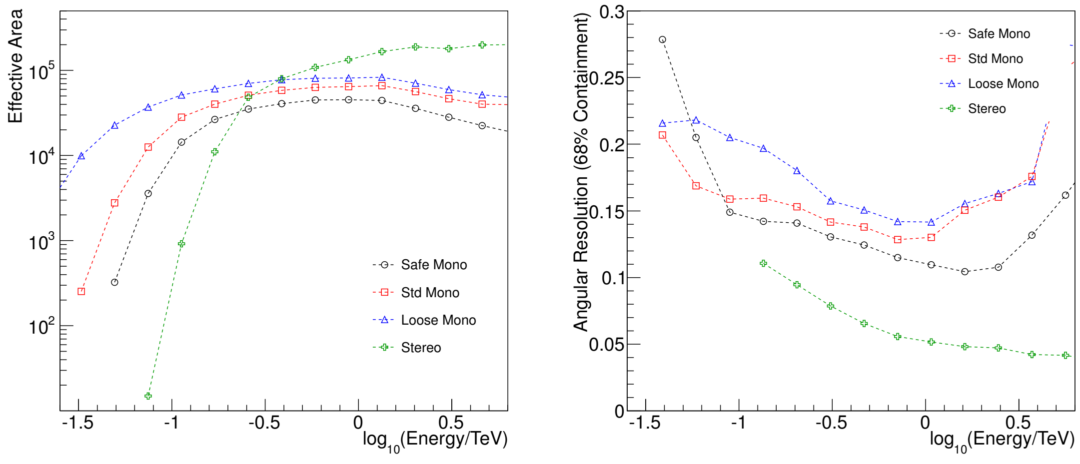

Figure 2: Angular resolution (68% containment radius calculated from a double gaussian fit) and effective collection area as a function of the simulated gamma-ray energy, for the of the ImPACT *mono* and *stereo* analyses for a simulated point-like source of gamma-rays at 20° zenith angle.

3. Performance

3.1 Simulated Data

In order to demonstrate the performance of the ImPACT analysis with H.E.S.S. II, tests were first made using simulated data. In this case a point-like source of gamma-rays was simulated at 20° zenith angle. Figure 2 summarises the performance of the ImPACT analysis for both the mono and stereo event classes.

Comparison of the effective areas shows that, as expected, the mono analyses are able to retain relatively large effective areas down to low energies (figure 2). The best low energy performance can be achieved with the loose cuts, retaining 10^4 m^2 of effective area down to 30 GeV. With *std* and *safe* cuts the low energy area is somewhat reduced due to the harder cuts being used. These harder cuts however, lead to significant improvements that can be seen in the angular resolution of these cut-sets with an angular resolution of below 0.16° seen for most of the energy range, in comparison to $\sim 0.2°$ resolution of the *loose* cuts. For the mono analyses there is generally an improvement in angular resolution with event energy, however once an energy of around 2 TeV is reached shower images are often truncated at the edge of the cameras reducing the reconstruction performance.

Config	Amp	Npix	Local distance	θ^2 (deg^2)	ζ	MSCW	MSCL
ImPACT mono **Safe**	80	8	1.15°	0.015	>0.9	n/a	n/a
ImPACT mono **Std**	60	6	1.15°	0.024	>0.78	n/a	n/a
ImPACT mono **Loose**	40	4	1.15°	0.045	>0.44	n/a	n/a
ImPACT stereo	70, 75	n/a	2°, 1.15°	0.0075	n/a	<0.6	<1.9

Table 1: Image selection and background rejection cuts for the three H.E.S.S. mono cut configurations compared in this paper.

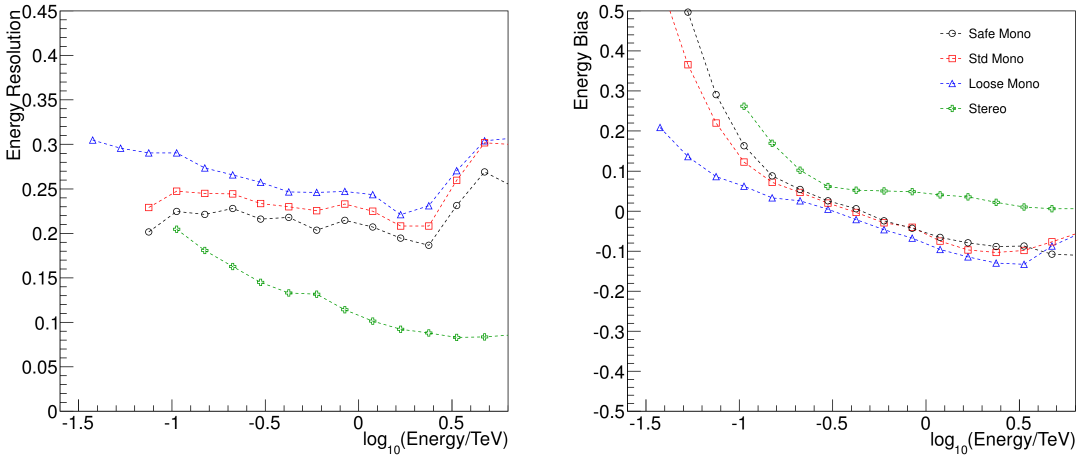

Figure 3: Energy reconstruction performance of the H.E.S.S. II ImPACT analyses shown by the energy bias (left) and resolution (right) as a function of the simulated event energy.

Similar improvements can be seen in the performance of energy reconstruction (figure 3). The energy biases of all 3 mono cut sets shows some gradients, overestimating the energy of low energy events, and underestimating at high energies. These biases are due to the difficulties in breaking ambiguities between the impact distance and energy for mono events.

Stereo analysis on the other hand, has quite poor effective area at the lowest energies, due to the requirement of images in at least 2 telescopes. Above 300 GeV the use of the 4 H.E.S.S. I telescopes in the analysis allows for a significantly improved effective area. It is clear from the all performance curves that the use of 2 telescopes in the fit procedure is extremely helpful to the reconstruction at all but the lowest energies, resulting in angular and energy resolutions much improved over the mono reconstruction across the full stereo energy range. Therefore, in the majority of cases more accurate event reconstruction can be achieved using information from CTs 1-4 whenever available, even when only very small images are available in these telescopes.

3.2 Crab Nebula Observations

Tests were also made using the ImPACT analysis using 7.2 hours of Crab Nebula observations taken in late 2014. Figure 4 shows the results of this analysis using the std ImPACT mono analysis chain. These observations were taken at an offset angle of 0.5° from the camera centre and a mean zenith angle of 47°. In this observation time the Crab Nebula was seen at a significance of more than 96σ, with an excess of over 7700 γ-like events and a signal-to-background ratio of 2.3. The resultant significance map is well normalised showing a point-like source at the expected position.

Figure 5 shows the distribution of these excess events as a function of reconstructed event energy. This distribution shows excess events down to 100 GeV (in comparison with the 300-400 GeV energy threshold seen in [5]), with the majority of events being seen at the lowest energies ($<$ 300 GeV). However, in the case of such a strong source, significant emission is seen up to several TeV. A spectral fit was made to this data using a log parabolic model of the form $\phi_0 \left(\frac{E}{E_0}\right)^{-[\alpha+\beta \ln(E/E_0)]}$. The log parabola gave an acceptable fit, finding best fit parameters of $\phi_0 =$

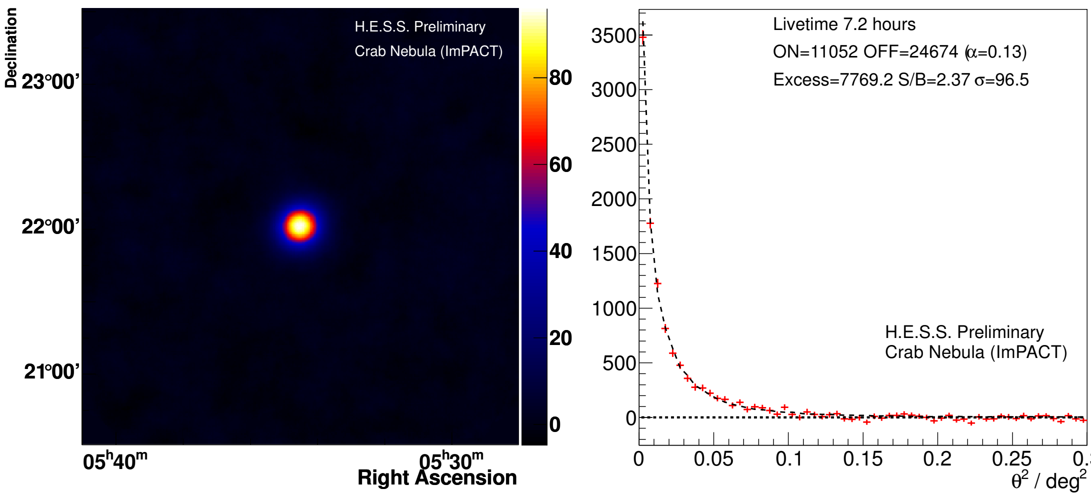

Figure 4: Significance map of the Crab Nebula region using an event correlation radius of 0.1° (left) and distribution of squared angular distance of excess events from the Crab Nebula position (right), black dashed lines shows the expected PSF from simulations (assuming a power-law spectral index of -2.4, normalised to number of counts in central 0.1 deg^2).

$3.951 \pm 0.09 \times 10^{-11}$ cm^{-2}s^{-1}TeV^{-1}, $\alpha = 2.49 \pm 0.03$ and $\beta = 0.203 \pm 0.02$, when $E_0 = 1$ TeV (Figure 6). This spectral fit matches well with both previously published H.E.S.S. results [5] and analyses of the same data set using other analysis chains.

3.3 Conclusion

We have demonstrated the adaptation of the high performance event reconstruction algorithm ImPACT to work with the mixed telescope type H.E.S.S. II array. This algorithm has proven both reliable and accurate for H.E.S.S. II data analysis behaving well on both simulations and analysis of Crab Nebula data.

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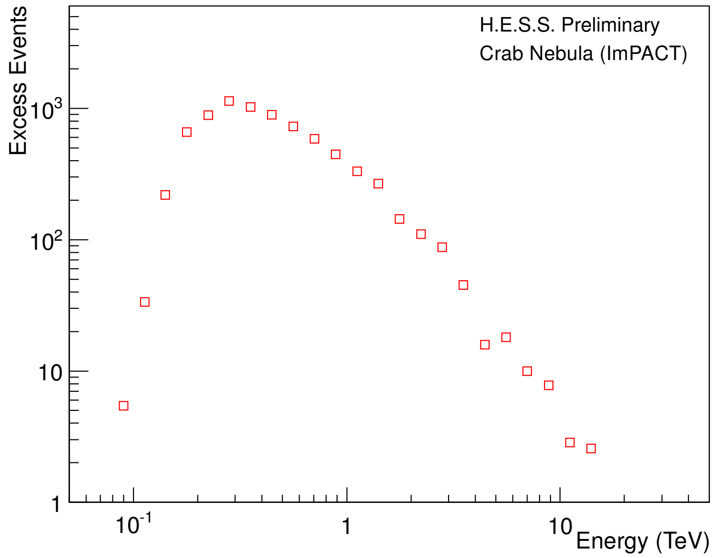

Figure 5: Excess event distribution as a function of reconstructed event energy for 7.2 hours of Crab Nebula observations using std ImPACT mono cuts.

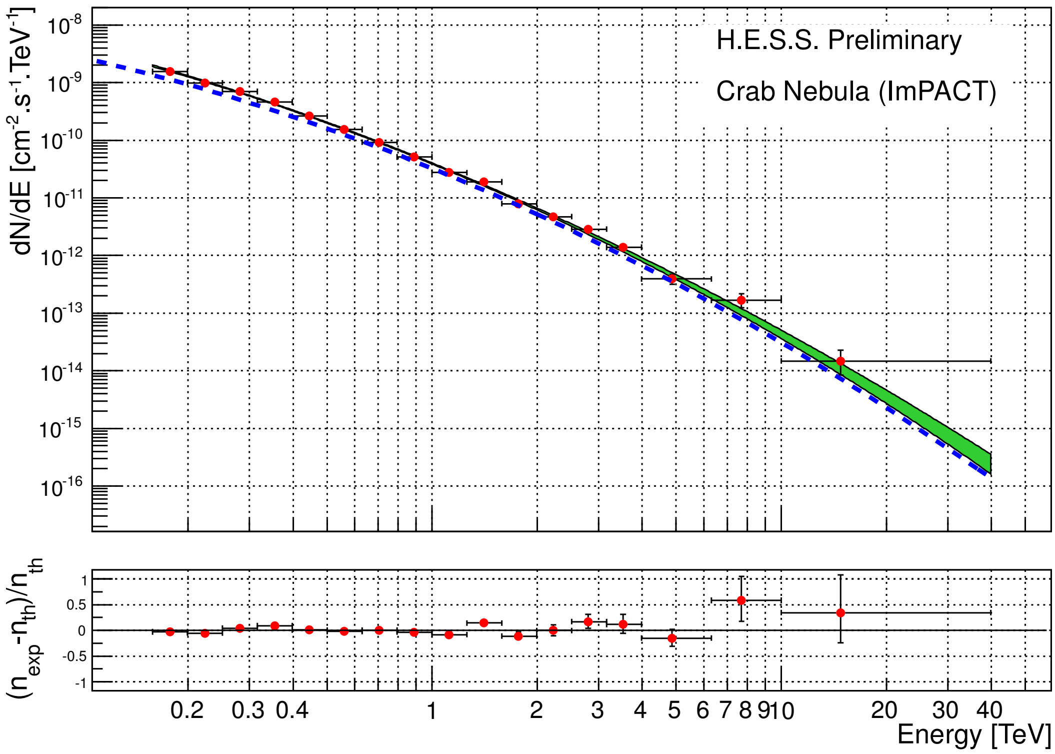

Figure 6: Spectral fit of the Crab Nebula data assuming a log parabolic model. Blue line shows the spectrum obtained by the MAGIC II telescope[8]

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